

Design and Operation of a 10 MWe Supercritical CO₂ Recompression Brayton Power Cycle



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Annual AIChE Meeting, San Francisco, CA, November 13-18, 2016



Presentation Overview

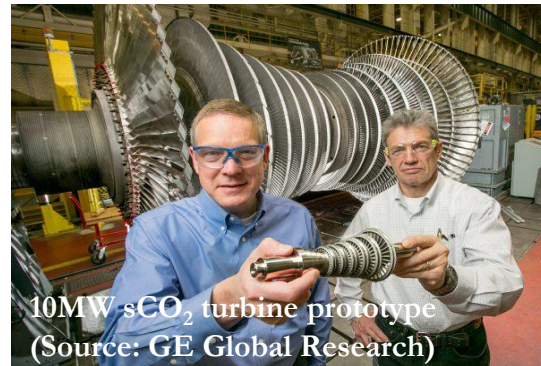
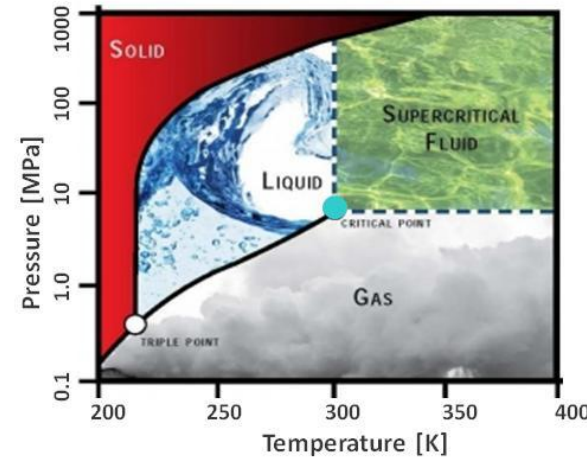
- **Introduction**
- **Modeling**
 - sCO₂ Recompression Brayton Cycle Overview
 - Software Tools, Physical Properties, and Unit Operation Models
- **Simulation Results**
 - Steady-State Design of 10 MWe Cycle
 - Transient Studies
 - Open-loop turndown in heat input
 - Maximizing cycle efficiency during heat input turndown
 - Temperature, flow split, and inventory control
- **Conclusions and Future Work**

Supercritical CO₂ Brayton Cycles

Motivation

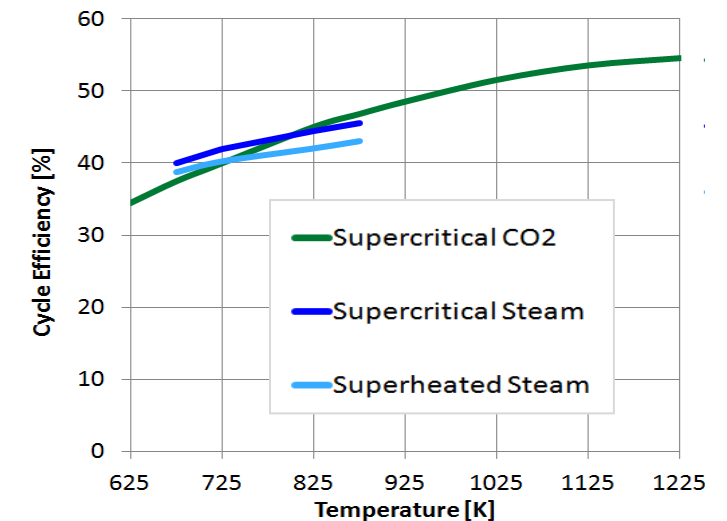
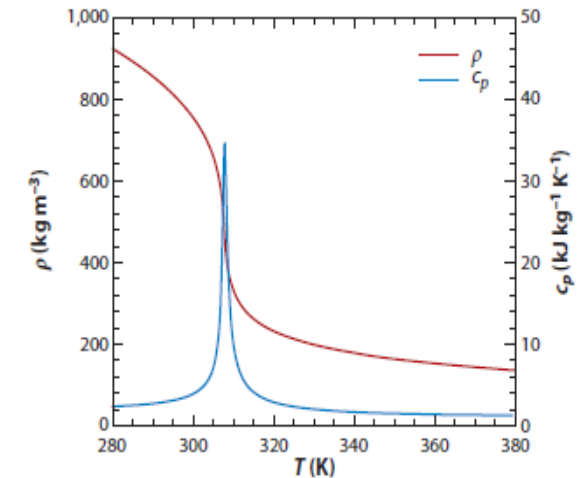
- **Gaining increasing attention as an attractive alternative to conventional Brayton and Rankine cycles using steam**

- Moderate conditions for supercritical state
- Higher density near critical point reduces compression load
- Power generation from turbine at higher temperatures
- Increased thermal efficiencies of 50% or greater
- Very high power density
- More compact design
- Offer lower capital cost, operating costs, and cost of electricity



- **Potential match for many different heat sources**

- Waste heat recovery, fossil energy, nuclear, and concentrated solar



U.S. DOE's Supercritical Transformational Electric Power (STEP) Program



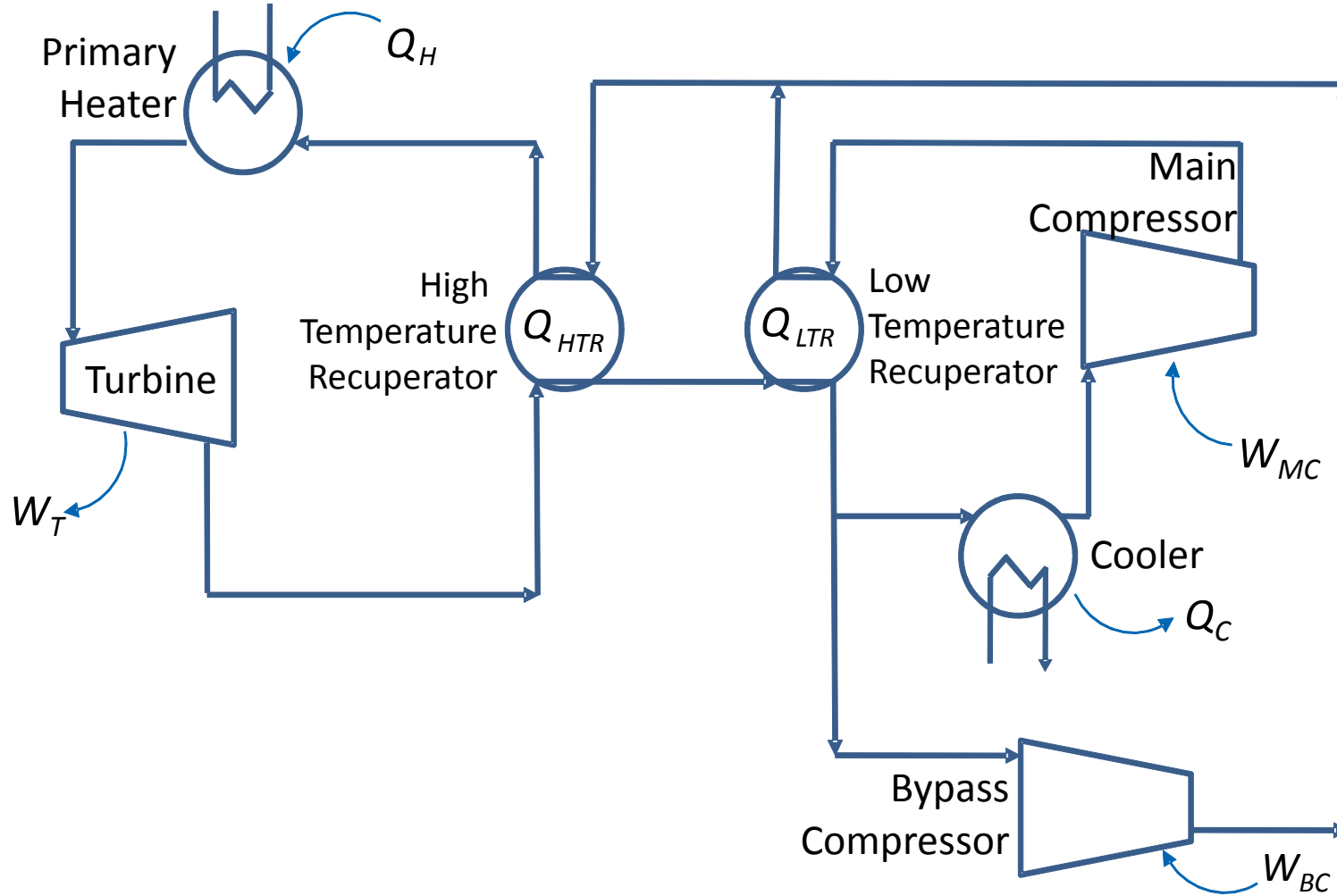
- Crosscutting DOE initiative to demonstrate sCO₂ power cycle at commercial scale
- **DOE announced project award to develop sCO₂ test facility (10/17/2016)**
 - \$80M federal contribution, 20% industry cost share, and 6-year duration
 - Managed by team led by Gas Technology Institute, Southwest Research Institute, and General Electric Global Research
 - Design, build, and operate 10 MWe sCO₂ Pilot Plant Test Facility in San Antonio, TX
 - Closed, indirect, sCO₂ recompression Brayton cycle
 - Turbine inlet operating temperature of 973.15 K (700 °C)
- **Demonstrate steady-state, dynamic, load-following, startup, and shutdown operations**

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Closed Indirect sCO₂ Recompression Brayton Cycle

Simplified Block Flow Diagram



Key Features

- Closed cycle
- Indirect heat source
- Two stages of recuperation
- Cooler to reject unused heat
- Parallel compressors
- Decoupled turbomachinery

sCO₂ Recompression Brayton Cycle

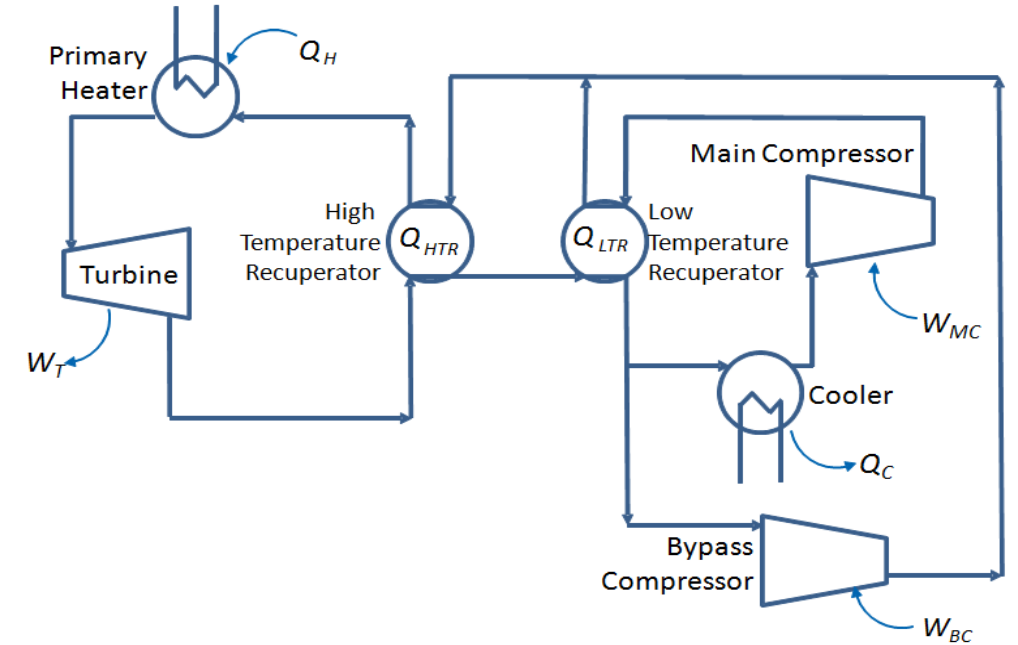
Modeling : Software and Physical Properties

- **Software Tools**

- Steady-state: Aspen Plus v8.8
- Dynamics: Aspen Plus Dynamics v8.8
 - Equation-oriented, pressure-driven

- **Physical Properties**

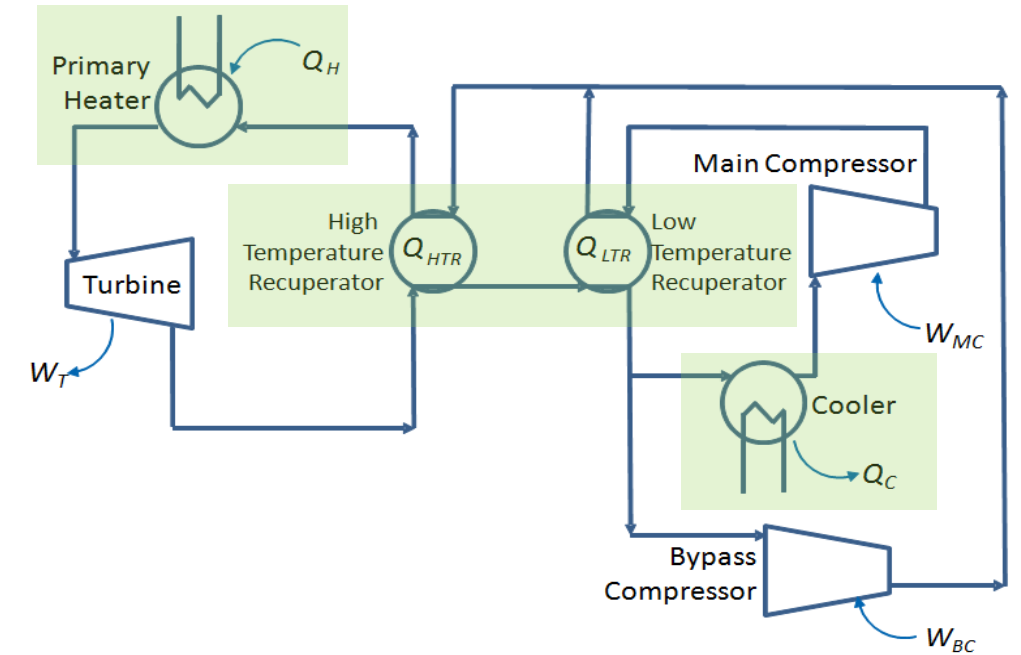
- Pure Component Database: APV88 PURE32
- Property Method: NIST REFPROP
 - Equation of state from Span and Wagner[†] (1996)



sCO₂ Recompression Brayton Cycle

Modeling: Heat Exchangers

- Shell-and-tube, countercurrent flow
- Temperature specifications
 - Primary heater outlet T [same as turbine inlet T]
 - **Design T = 973.2 K (1292 °F) [material constraint]**
 - Recuperators
 - Hot outlet – cold inlet, $\Delta T = 10 \text{ K (18 °F)}$
 - Cooler
 - CO₂ hot outlet T = 308.1 K (95 °F) [4 K above critical T]
 - Cooling water inlet T = 295.1 K (71.5 °F)
 - Constant log mean temperature difference (LMTD)
- Flow-dependent pressure drop correlation
 - $\Delta P = kW^2(1/\rho_{in} + 1/\rho_{out})/2$, where $k = 2000$
- Dynamic Options/Specifications
 - Volume = (residence time)*(steady-state volumetric flowrate)
 - Metal masses calculated using Aspen Exchanger Design and Rating (EDR)



sCO₂ Recompression Brayton Cycle

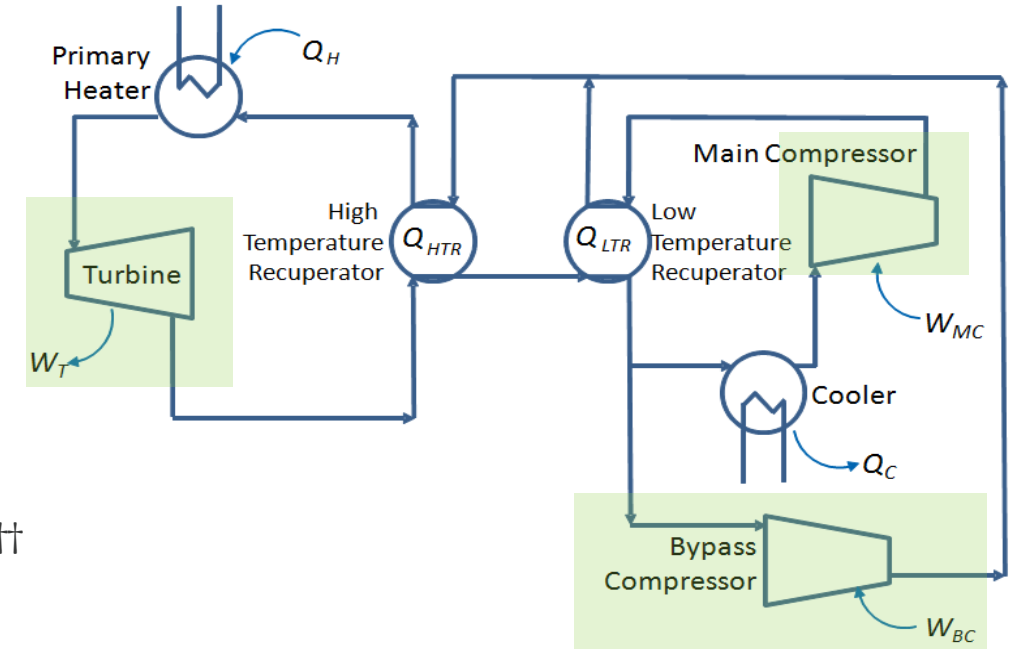
Modeling: Turbomachinery

- **Isentropic Calculations**

- Mollier-based method used to compute enthalpy change
- Efficiencies at design point
 - Turbine=0.85, Main Compressor=0.82, Bypass Compressor=0.78

- **Dynamics: Performance/Efficiency Curves**

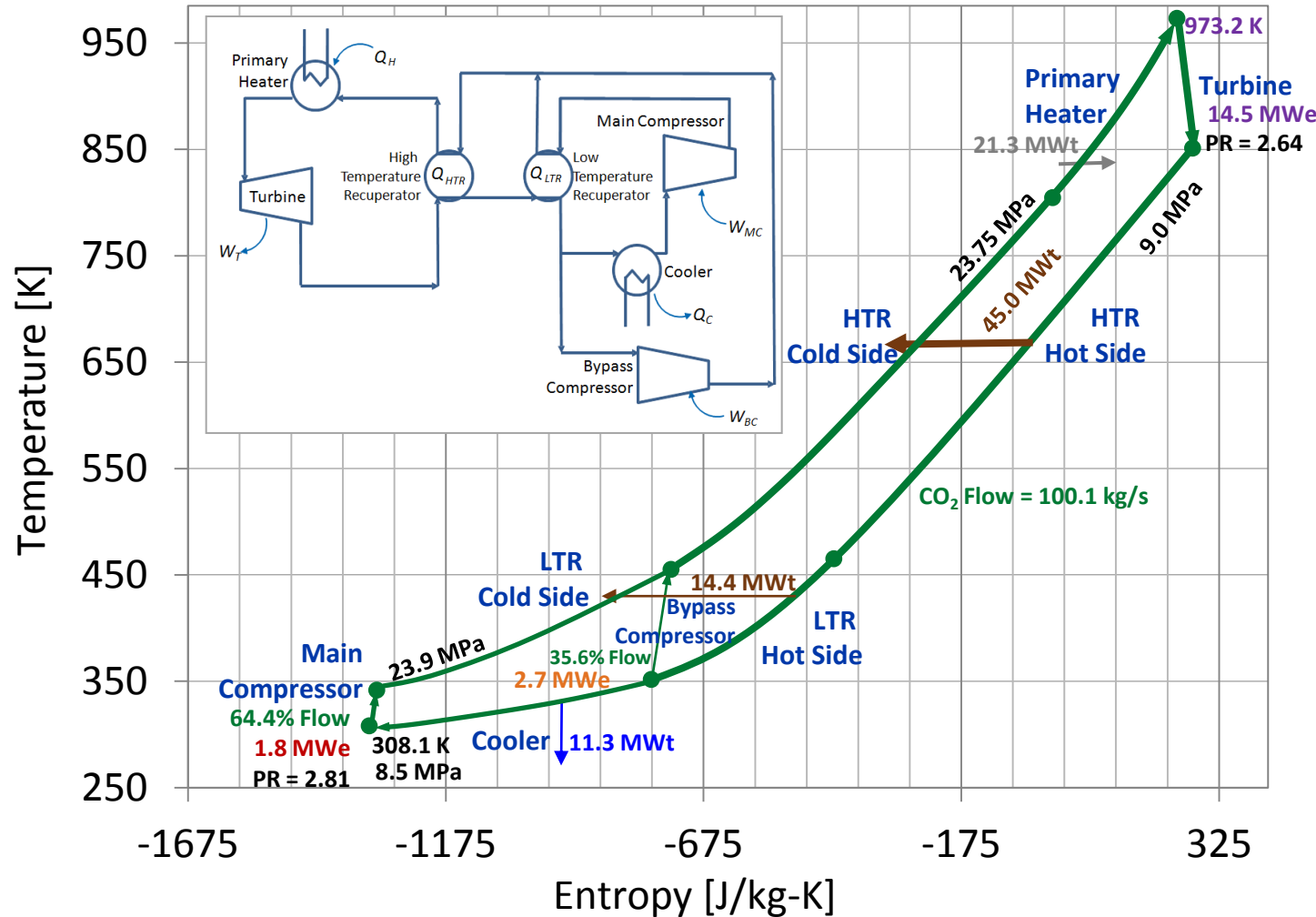
- Turbine curve scaled from data taken from turbine map for a kW-scale sCO₂ experimental system at Sandia National Laboratories (Pasch et al., 2012)[†]
- Compressor curve scaled from data taken from CCSI(2014)^{††}
- Scaling to design point (Tamiru et al., 2011)^{†††}
 - Pressure ratio (PR), $PR = (PR_{des}-1)/(PR_{map,des}-1)(PR_{map}-1) + 1$
 - Volumetric flow rate, $Q = (Q_{des}/Q_{map,des})(Q_{map})$
- Single performance curve at reference speed in Aspen Plus
 - Head vs. Volumetric flow rate at 300 Hz (18,000 rpm)
- Performance at speeds other than design vary based on fan laws in Aspen Plus Dynamics
 - $X/X_{ref} = (N/N_{ref})^{Exp}$, where N is shaft speed and fan law exponent, Exp , is 2 for $X=Head$, 3 for $X=Power$, and 1 for $X=Efficiency$



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10 MW sCO₂ Recompression Brayton Cycle Simulation Results: Steady-state Design Point

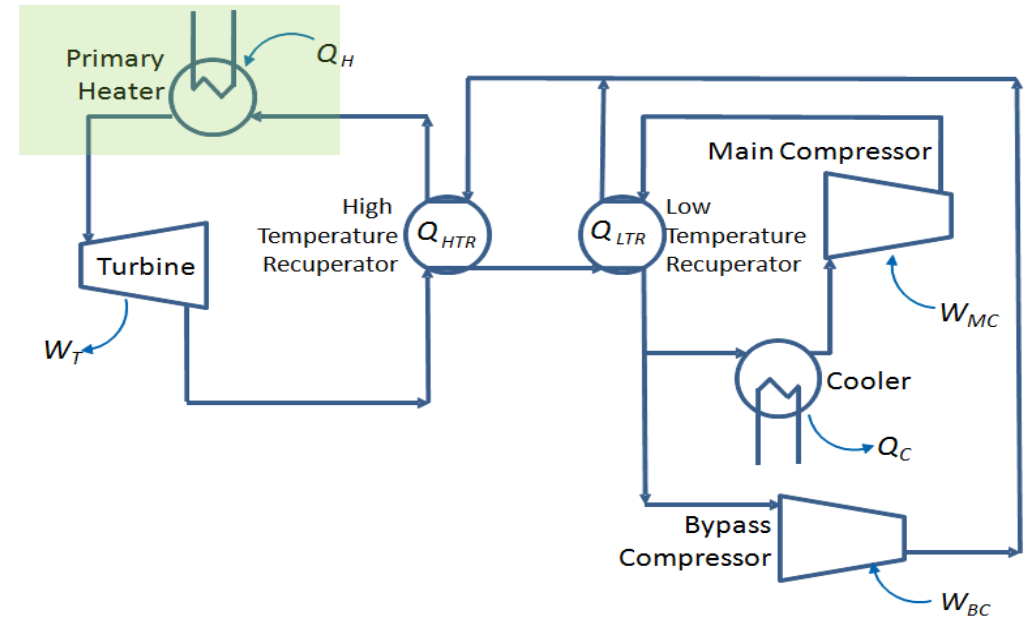


- Net power is 10 MWe.
 - $W_{NET} = W_T - W_{MC} - W_{BC}$
- Heat input is 21.3 MWt.
- Cooler rejects 11.3 MWt.
- Efficiency is 46.9%.
- Low pressure ratio (PR)
 - Turbine PR = 2.64 (23.75 MPa/ 9.0 Mpa)
- Cycle is highly recuperated.
 - $(Q_{HTR} + Q_{LTR}) / Q_H = 2.8$
 - $Q_{HTR} / Q_{LTR} = 3.1$
- Bypass compressor flow is ~1/3 of total CO₂ flow.

Step-Change Decrease (Turndown) in Heat Input

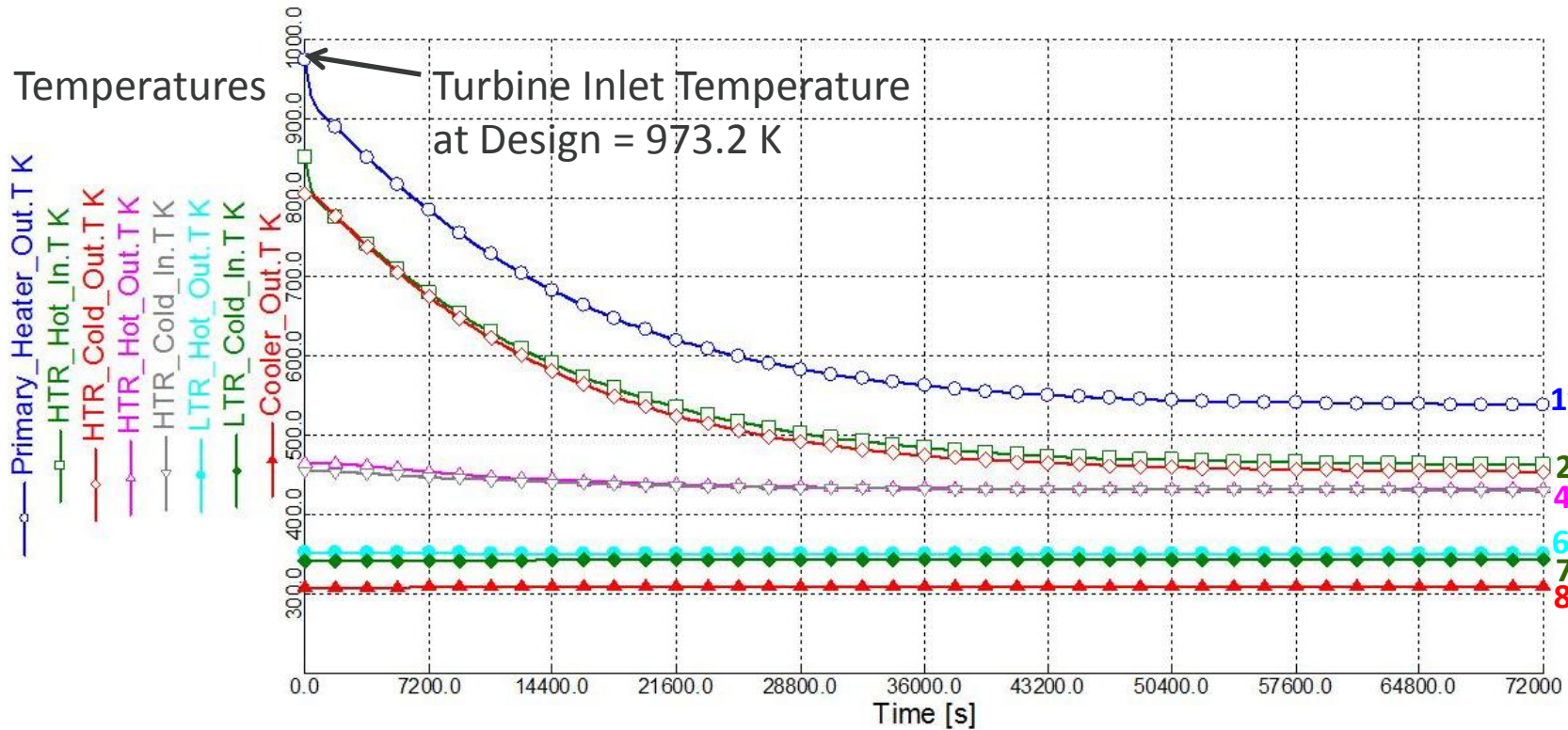
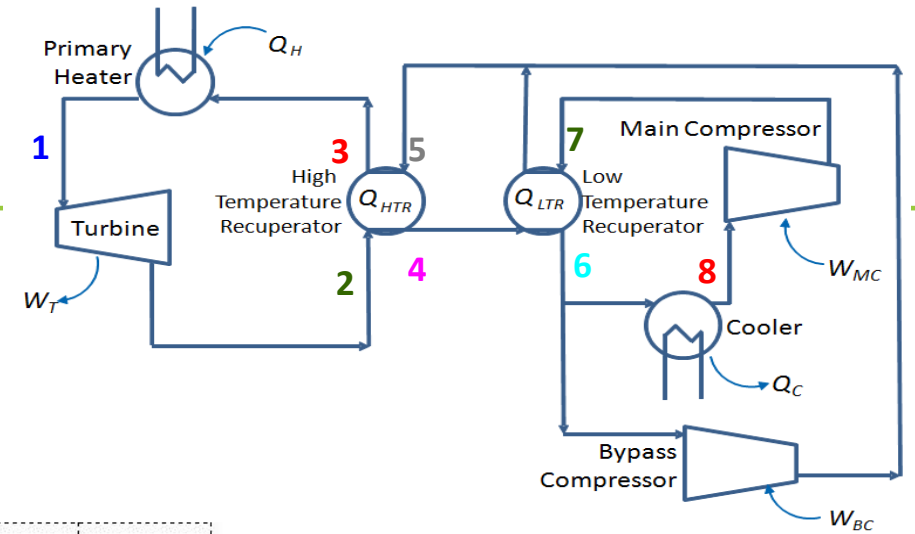
Open-Loop Dynamic Simulations

- Reduce heat duty in Primary Heater in a step-wise manner
- Determine maximum open-loop turndown (without controllers)
- Analyze dynamic response of open-loop cycle
 - Time required to reach new steady-state
 - Temperatures, pressures, and flows
 - Power requirements and thermal efficiency



40% Turndown - Open Loop Temperature Results

- Disturbance at Time = 0.0 s
 - Heat Input = 12.8 MWt (from 21.3 MWt)



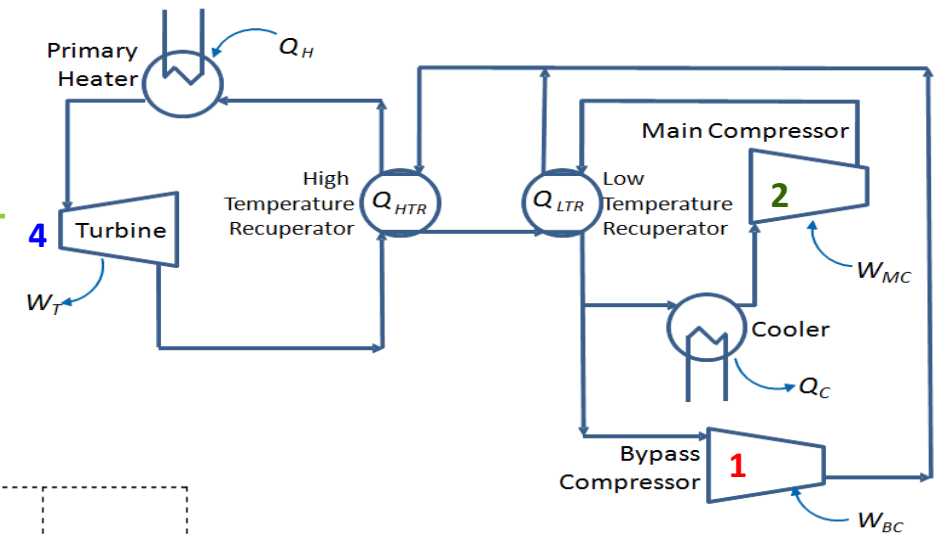
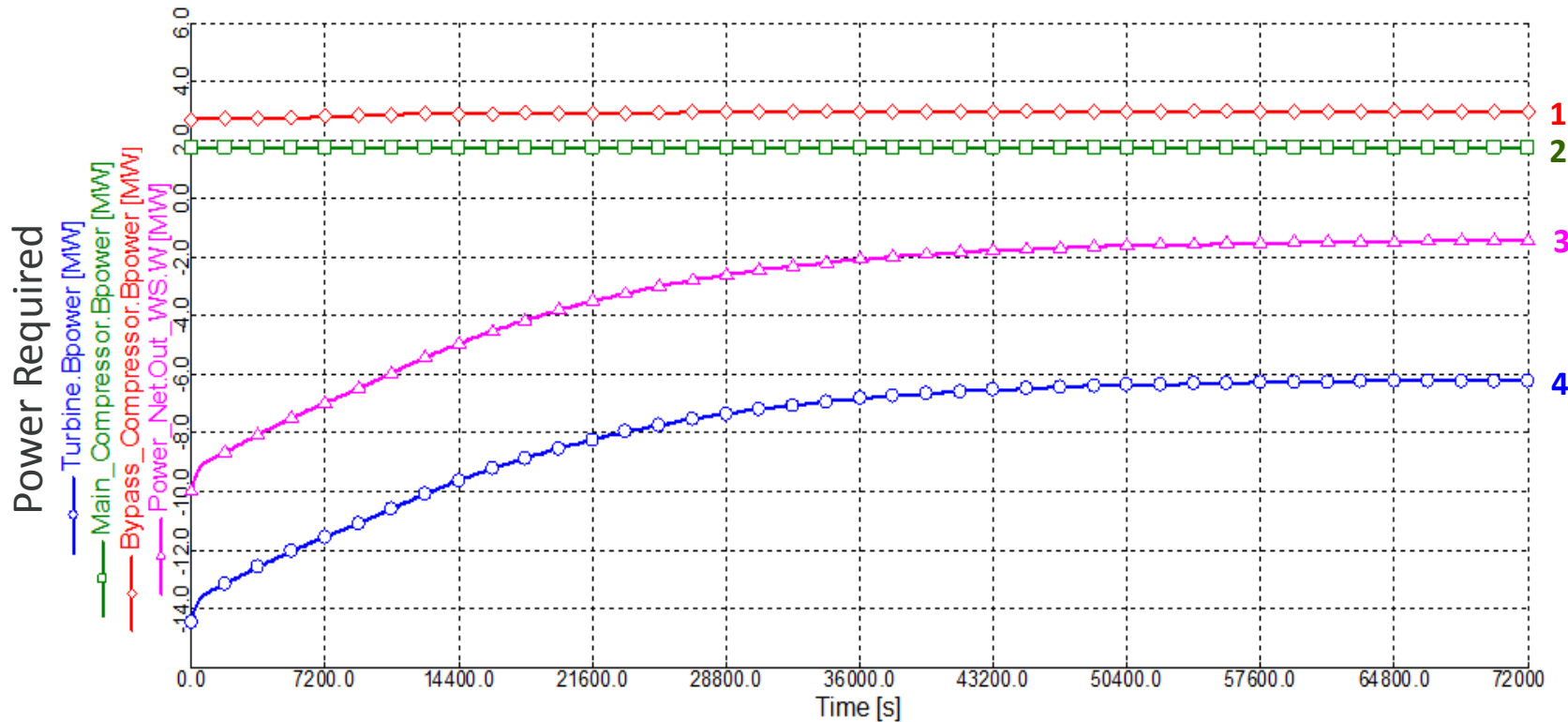
Turbine Inlet Temperature at Design = 973.2 K

Turbine Inlet Temperature at 40% Turndown = 538.4 K

Approaching temperature crossover in HTR

40% Turndown - Open Loop Turbomachinery Power Results

- Disturbance at Time = 0.0 s
 - Heat Input = 12.8 MWt (from 21.3 MWt)



- Steady-State Results
 - Net Power = 1.4 MWe
 - Efficiency = 10.9%

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Heat Input Turndown - Decoupled Turbomachinery

Temperature, Flow Split, and Inventory Control

- **Objective**

- Maximize cycle efficiency (net power/heat input)

- **Operating Constraints**

- **TIT \leq Upper bound** [MV1, MV2, MV3,]

- Design point, 973.2 K (material constraint)

- **Main compressor inlet T for CO₂ \geq Lower bound** [MV2]

- Design point, 308.1 K (4 K above critical T to avoid two-phase dome)

- **LTR Cold Side Exit T = Bypass Compressor Exit T** [MV3]

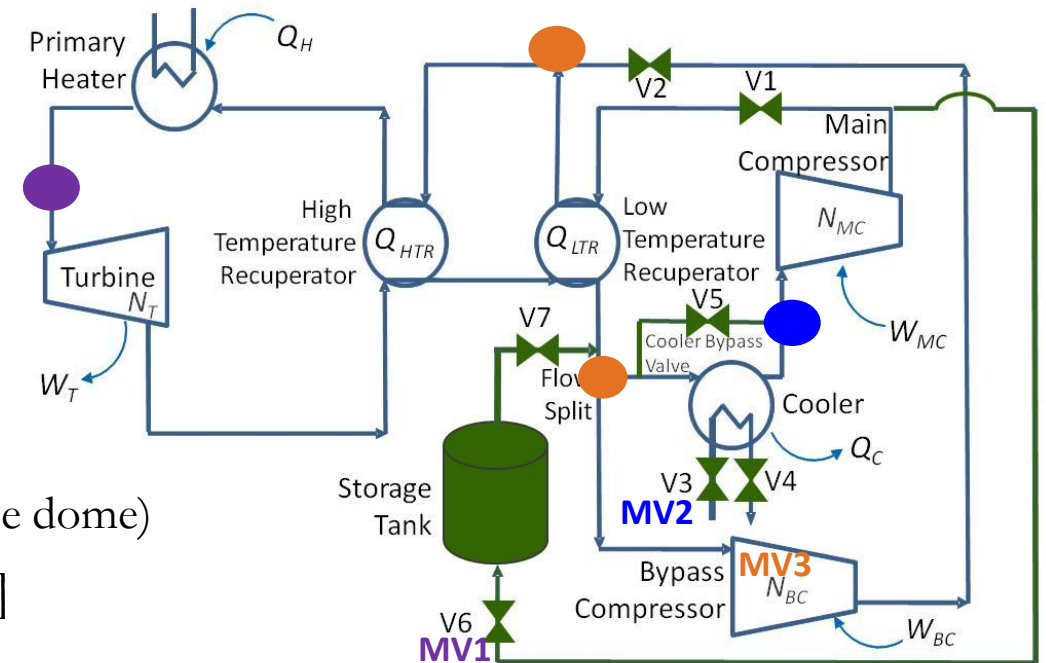
- Surge limit for bypass compressor

- **Manipulated Variables (MV)**

MV1: Storage valve (V6) | Inventory Control

MV2: Cooling water flow (V3) | Temperature Control

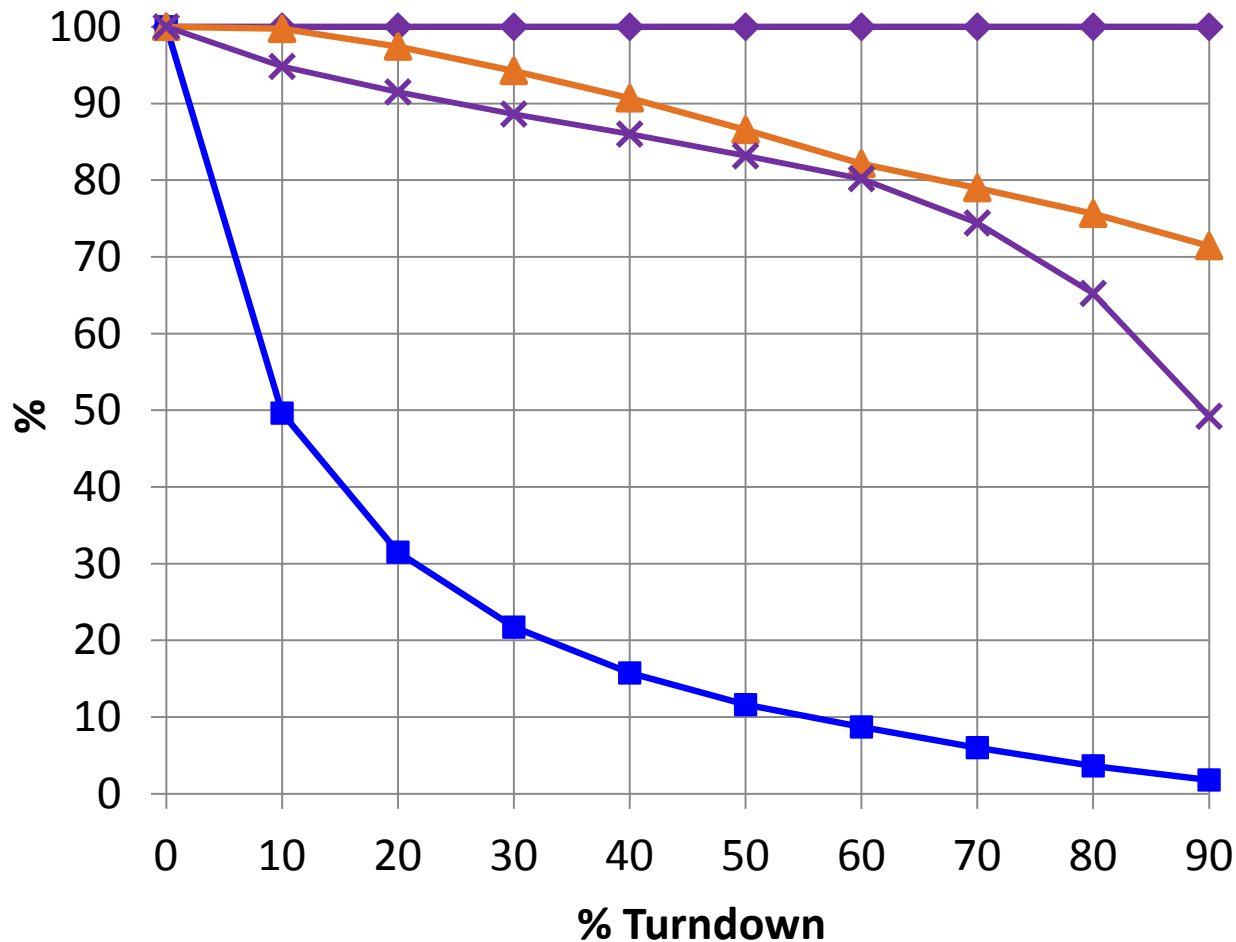
MV3: Bypass compressor speed (N_{BC}) | Flow Split Control



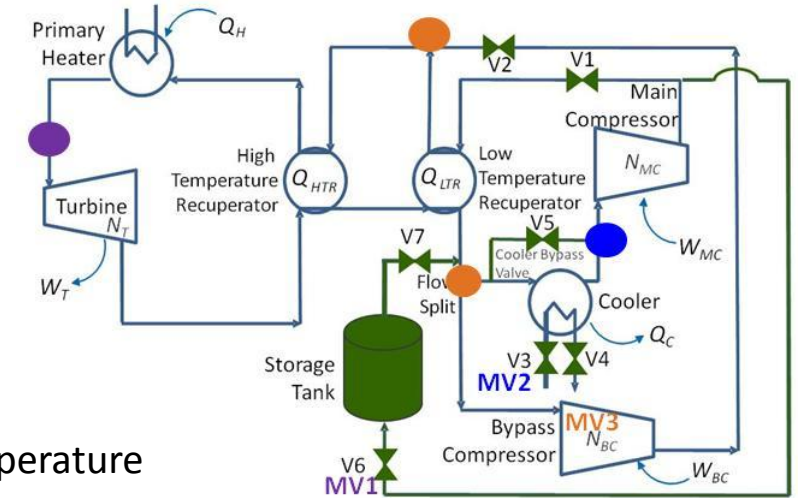
Heat Input Turndown - Decoupled Turbomachinery

Temperature, Flow Split, and Inventory Control

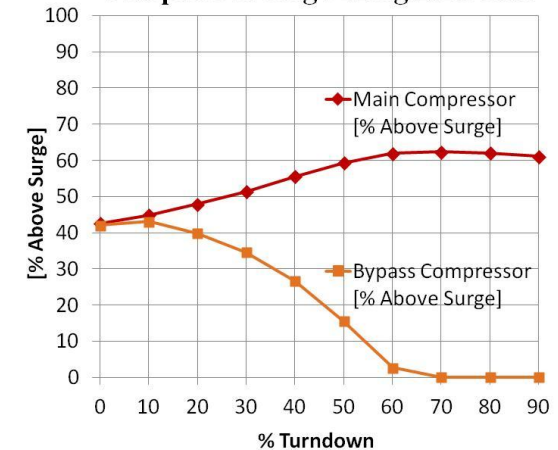
Objective and Manipulated Variable Profiles



- ◆ Turbine Inlet Temperature [% of Design]
- Cooling Water Flow [% of Design]
- ▲ Bypass Compressor Speed [% of Design]
- ✕ CO2 Storage [% of Cycle CO2 Mass]



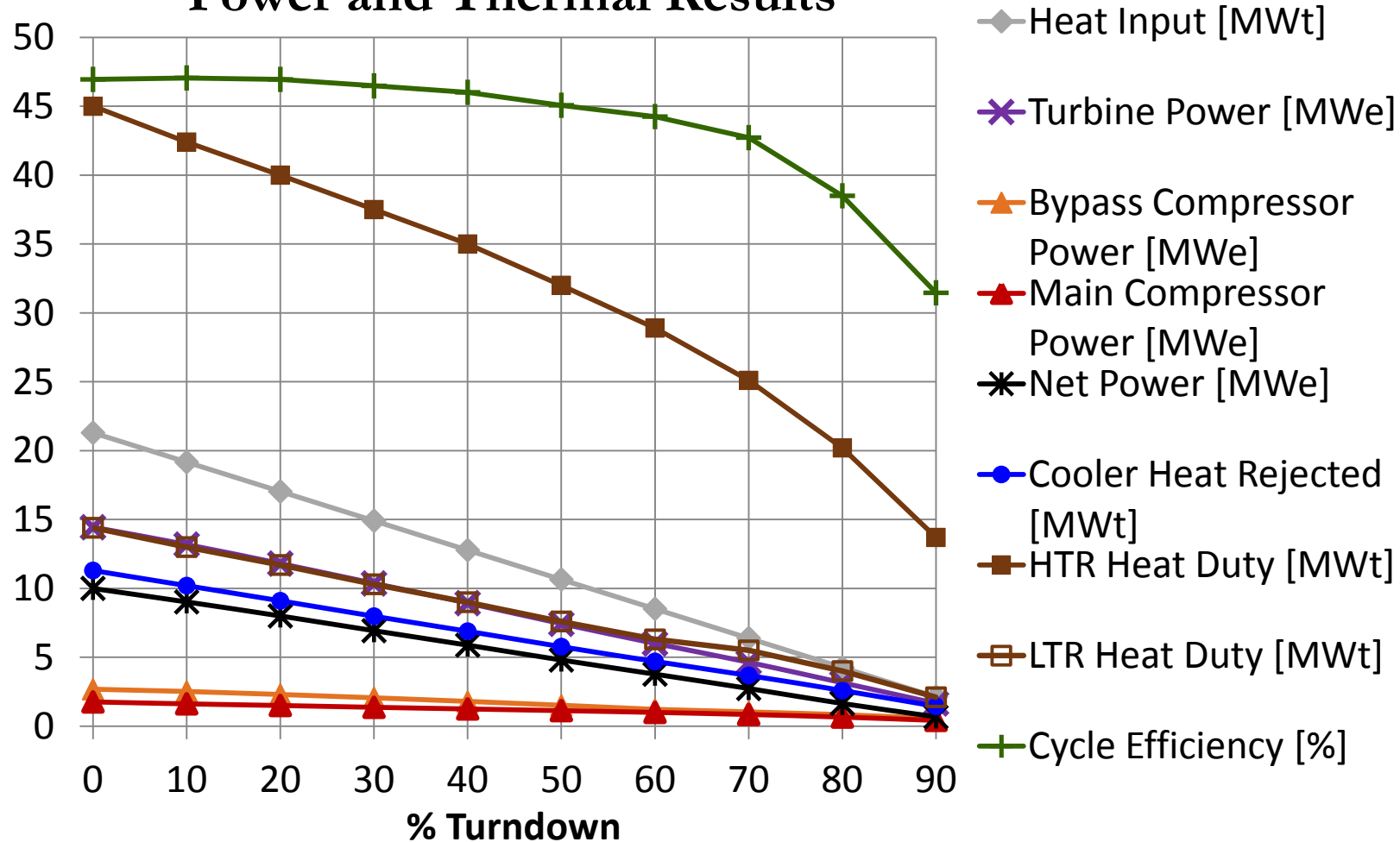
Compressor Surge Margin Results



Heat Input Turndown - Decoupled Turbomachinery

Temperature, Flow Split, and Inventory Control

Power and Thermal Results



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 - Maximizing cycle efficiency during heat input turndown
 - Decoupled vs. coupled turbomachinery
- **Conclusions and Future Work**

Conclusions

- Developed steady-state design and pressure-driven dynamic model of 10MWe sCO₂ recompression Brayton cycle
- Conducted transient studies for heat input turndown of open-loop cycle
- Analyzed operating strategies for maximizing cycle efficiency during heat input turndown, while satisfying process constraints
 - Inventory, flow split, and temperature control
 - 90% turndown while maintaining high efficiency

Future Work

- **Implement higher fidelity dynamic models of key components**
 - Multistage compressors
 - Enhanced turbine design and performance maps
 - Compact heat exchanger models with accurate heat transfer, mass holdup, and pressure drop calculations
- **Develop turbine control and compressor surge control**
- **Use advanced process control, including model predictive control**
- **Analyze operating and control strategies for other transient operation scenarios**
 - Startup and shutdown
 - Load-following operation and loss of load
- **Design optimal sensor network design for various tasks**
 - Disturbance rejection, state estimation, condition monitoring, fault diagnosis, ...
- **Exploit STEP pilot plant test facility**
 - Validate dynamic models, controls, and sensor network

Thank you!

Comments/Questions?

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Solutions for Today | Options for Tomorrow

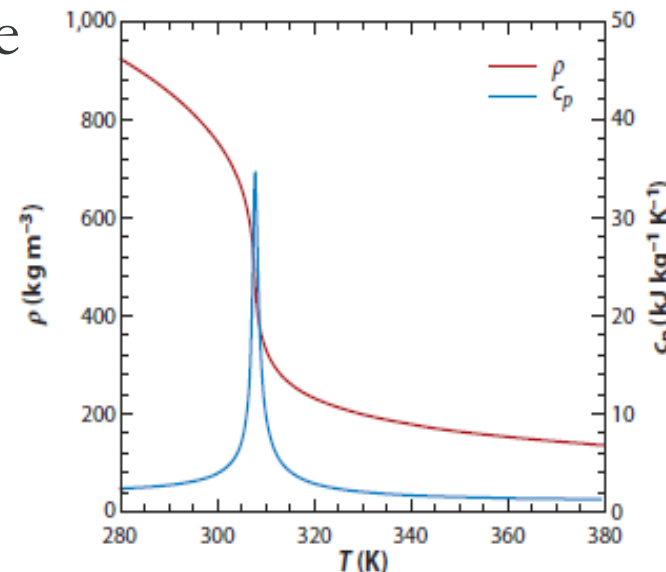
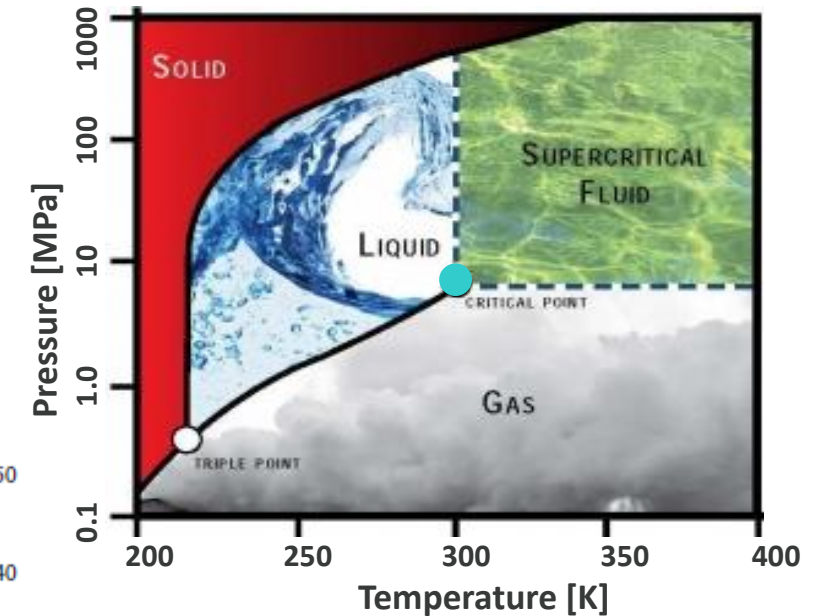


Extra Slides

Supercritical CO₂ Brayton Cycles

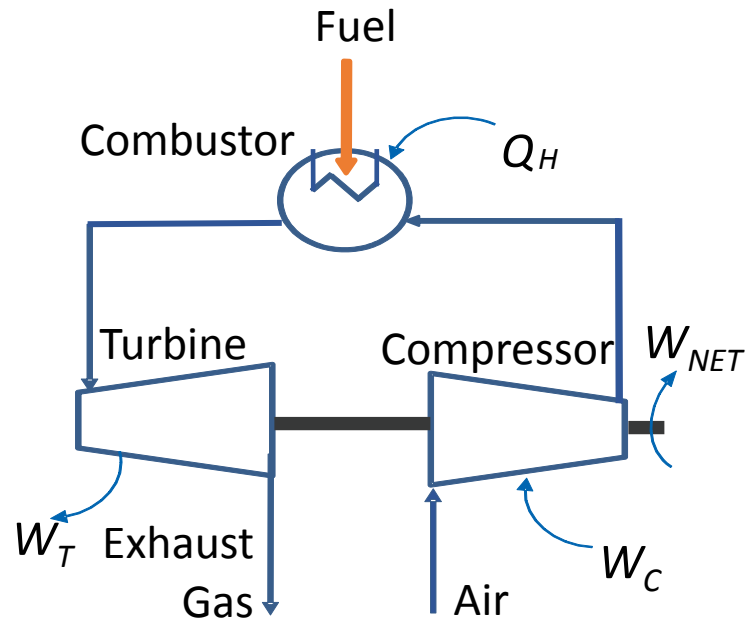
Motivation – CO₂ Physical Properties

- Moderate conditions for supercritical state
 - Critical Point ●
 - Temperature = 304.1K (87.9 °F)
 - Pressure = 7.4 MPa (1071.8psia)
- Excellent fluid properties
 - Liquid-like densities and gas-like viscosities around cycle
 - Increased density (ρ) and heat capacity (C_p) near critical point
- Less corrosive than steam
 - Enables power generation in turbine at higher temperatures



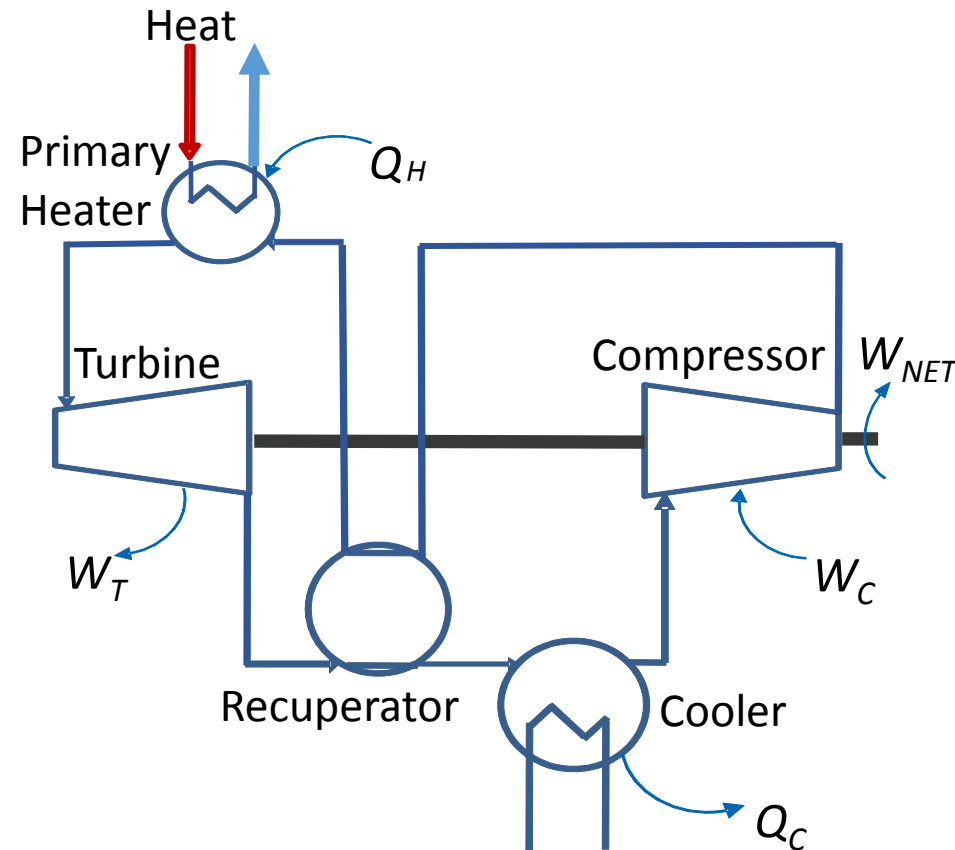
Brayton Power Cycles

Open, Direct



- Direct heating via combustion
- Air used as working fluid
- Fossil fuel-fired gas turbine power cycle

Closed, Indirect



- Indirect heating via external source
- Any gas or supercritical fluid can be used as working fluid
- Working fluid circulates in closed loop
- Recuperation used to pre-heat compressed working fluid with hot turbine exhaust
- Cooler rejects heat that is not converted to power

sCO₂ Recompression Brayton Cycle Challenges – System Design and Operation

- Develop and demonstrate viability of turbomachinery and heat exchange components
- Design, integrate, and scale up technologies for deployment of commercial-scale cycles
- Accommodate wide range of design/operation parameters and heat source applications
- **Develop operating procedures and process controls**
 - Maintain operation with CO₂ working fluid in supercritical region and cope with highly nonlinear fluid property changes, especially at cooler exit and main compressor inlet
 - Operate commercial-scale cycles with coupled, constant-speed turbomachinery
 - Operate main and bypass compressors in parallel
 - Cope with high degree of heat recuperation and pressure interactions
 - Manage cycle response to disturbances that impact thermal or pressure conditions



1 MW_{th}-scale sCO₂ Brayton test loop
(Source: Sandia National Laboratories)

Summary of Thermal/Power Results

Design Case vs. Open-Loop Heat-Input Turndown Cases

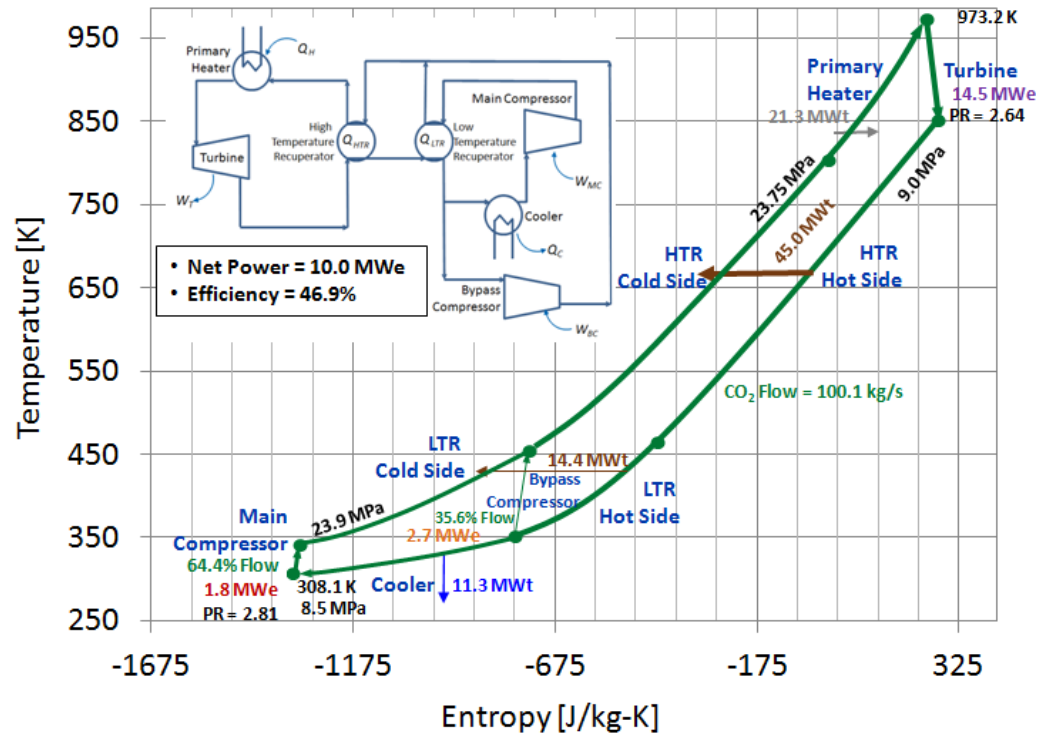
% Decrease in Heat Input	0%	10%	20%	30%	40%
Heat Input [MWt]	21.3	19.2	17.0	14.9	12.8
HTR Heat Duty [MWt]	45.0	33.1	21.7	12.6	4.0
LTR Heat Duty [MWt]	14.4	13.4	12.6	12.2	11.9
Cooler Heat Rejected [MWt]	11.3	11.3	11.4	11.4	11.4
Turbine Power Generated [MWe]	14.5	12.5	10.4	8.3	6.2
Main Compressor Power [MWe]	1.8	1.8	1.8	1.8	1.8
Bypass Compressor Power [MWe]	2.7	2.8	2.9	2.9	3.0
Compressor Bypass Fraction [%]	35.6	36.5	37.4	37.7	37.9
Cycle CO ₂ Flow [kg/s]	100.1	103.6	106.7	109.3	111.3
Cycle Net Power [MWe]	10.0	7.9	5.7	3.6	1.4
Cycle Thermal Efficiency [%]	46.9	41.2	33.5	24.2	10.9

- Maximum turndown of approximately 40%
- HTR absorbs most of the heat turndown
- Cooler heat rejected stays fairly constant
- Main compressor power required is constant
- Bypass compressor power required increases
- Cycle net power approaches breakeven point

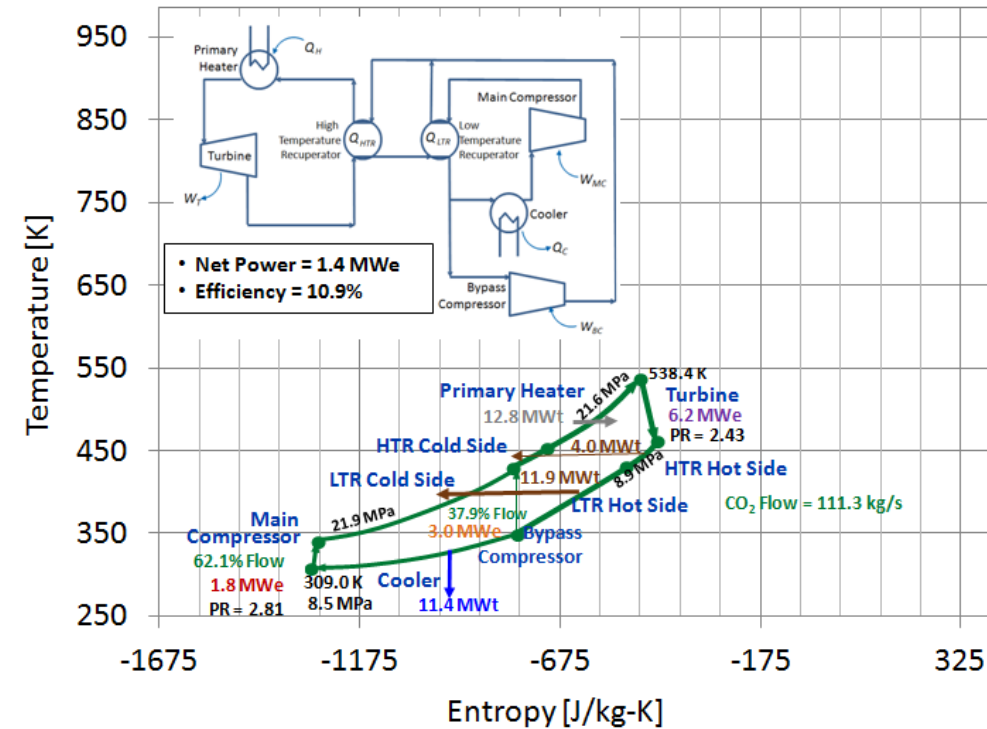
Heat Input Turndown - Open Loop

Temperature vs. Entropy Diagram

0% Turndown - Design

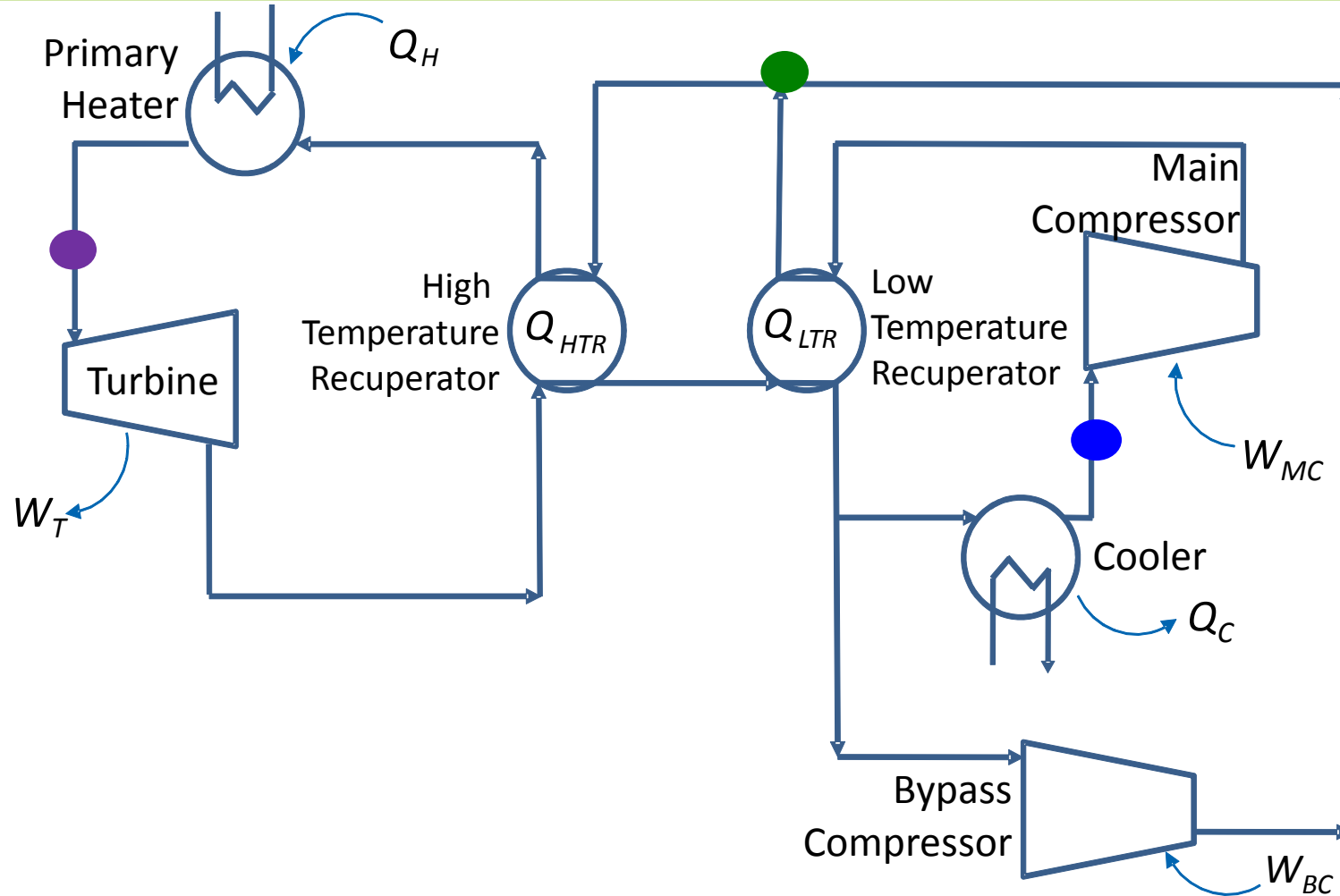


40% Turndown



Conclusion: Analyze strategies for maximizing cycle net power and efficiency by maintaining turbine inlet temperature (TIT) during heat input turndown

Heat Input Turndown for sCO₂ Recompression Brayton Cycle Control Problem Overview



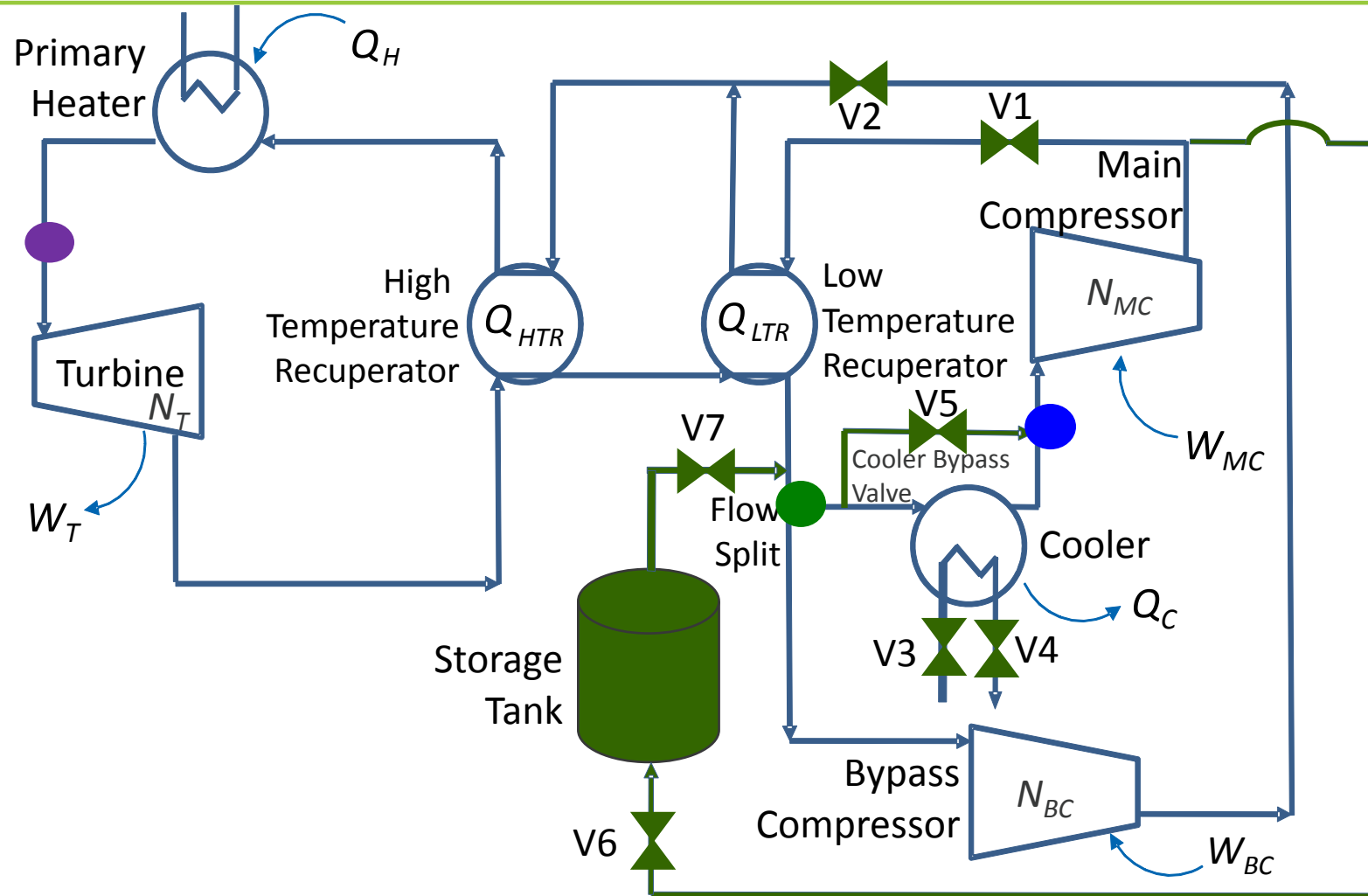
- **Overall Objective**

- Maximize cycle efficiency (net power/heat input)

- **Control Objectives and Operating Constraints**

- **●** TIT \leq Upper bound
 - Design point, 973.2 K (material constraint)
- **●** Main compressor inlet T for CO₂ \geq Lower bound
 - Design point, 308.1 K (4 K above critical T)
- **●** LTR Cold Side Exit T = Bypass Compressor Exit T
 - Maintain compressor operations above surge limits

Heat Input Turndown for sCO₂ Recompression Brayton Cycle Control Strategies



- **Objective**

- Maximize cycle efficiency (net power/heat input)

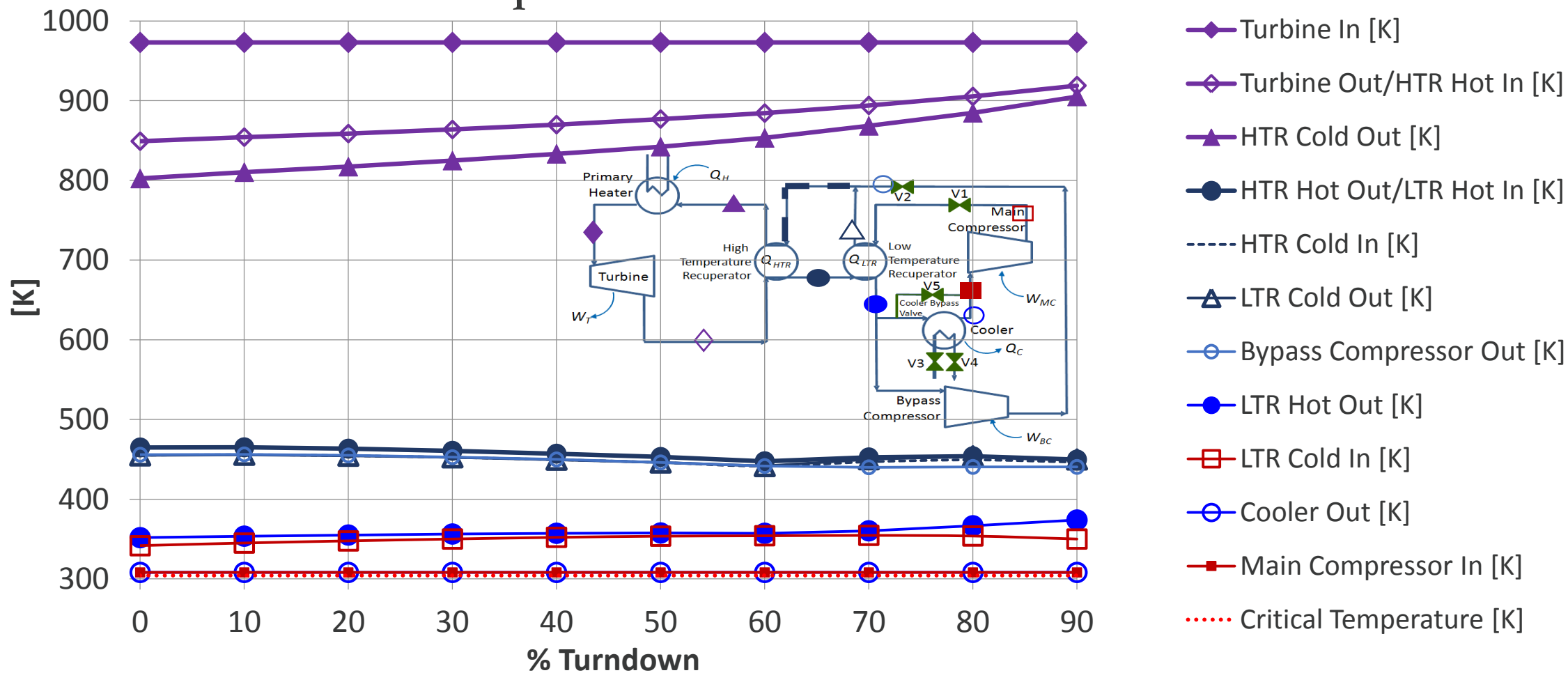
- **Control Strategies**

- **Temperature control**
 - Cooling Water Flow (V3)
 - Cooler Bypass (V5)
- **Flow split control**
 - Compressor speeds (N_{MC} , N_{BC}) for decoupled turbomachinery
 - Compressor valves (V1, V2) for coupled turbomachinery
- **Inventory control**
 - Turbomachinery speeds (N_{MC} , N_{BC} , N_T)
 - Storage (V6, V7)

Heat Input Turndown - Decoupled Turbomachinery

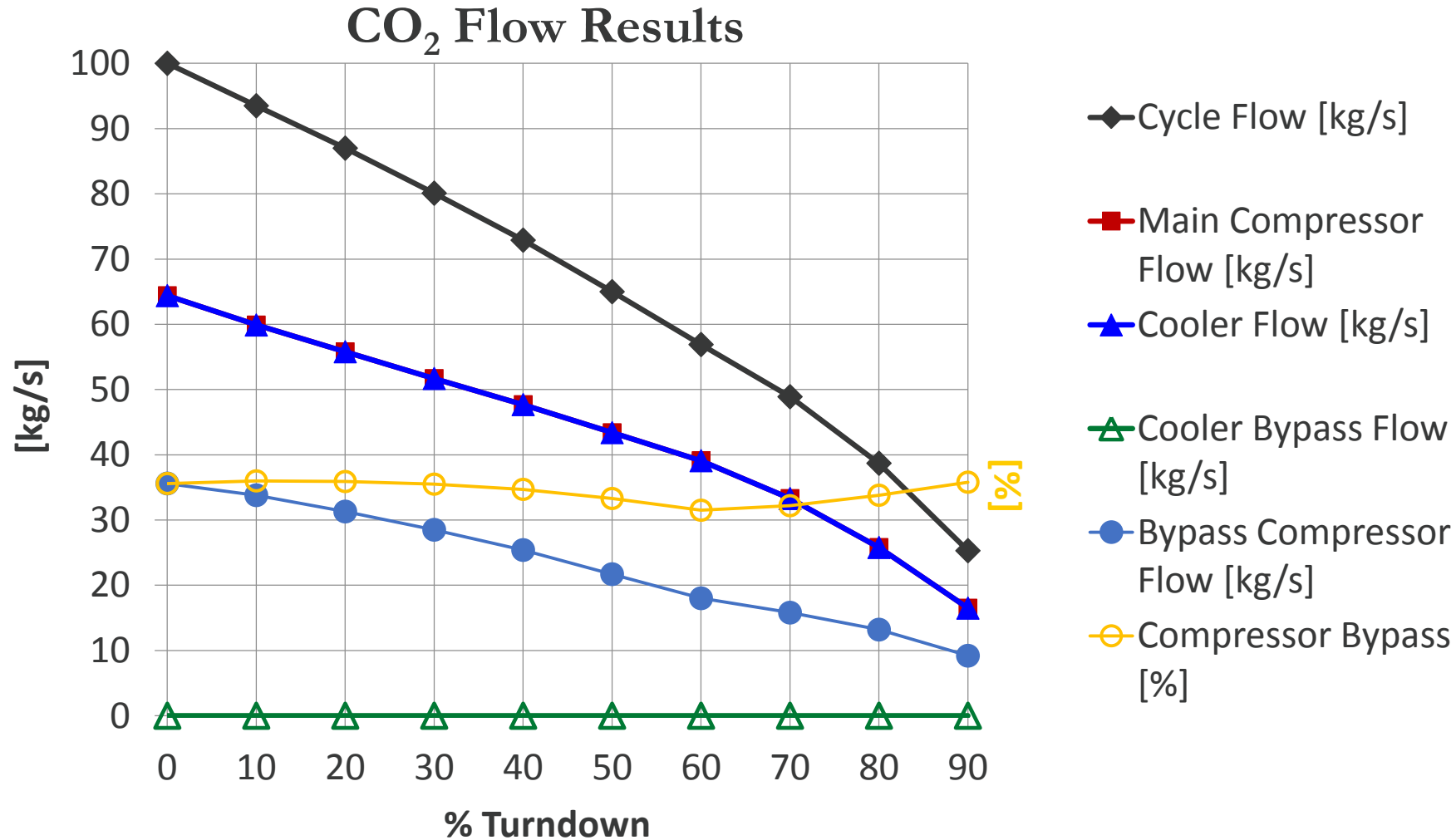
Temperature, Flow Split, and Inventory Control

Temperature Results



Heat Input Turndown - Decoupled Turbomachinery

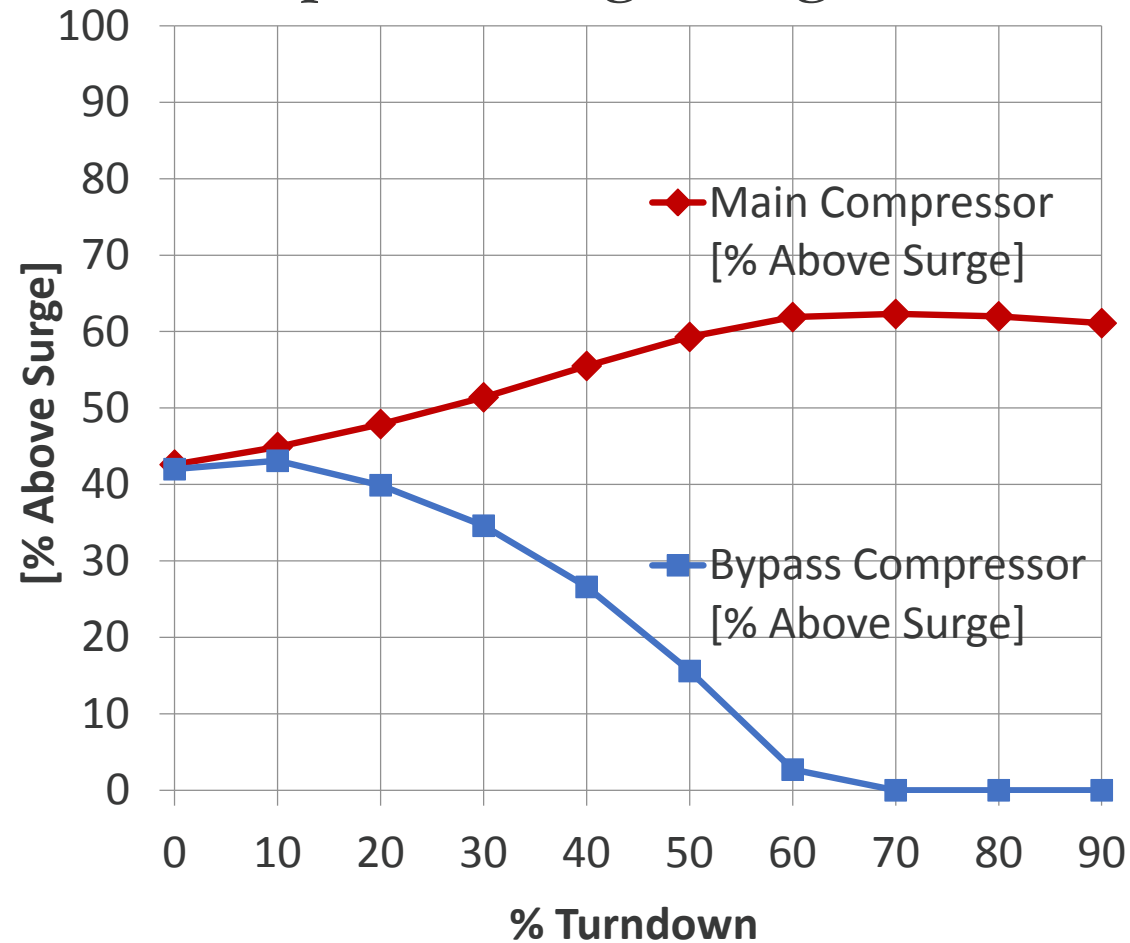
Temperature, Flow Split, and Inventory Control



Heat Input Turndown - Decoupled Turbomachinery

Temperature, Flow Split, and Inventory Control

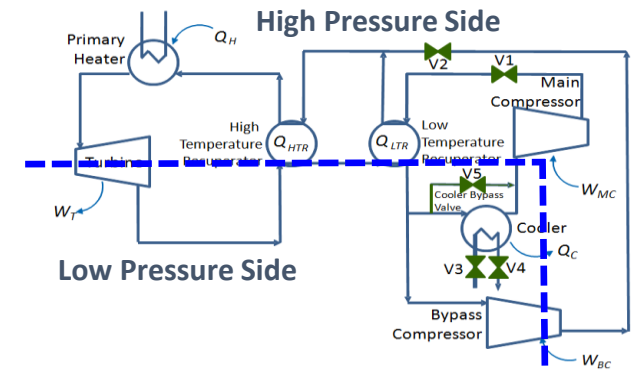
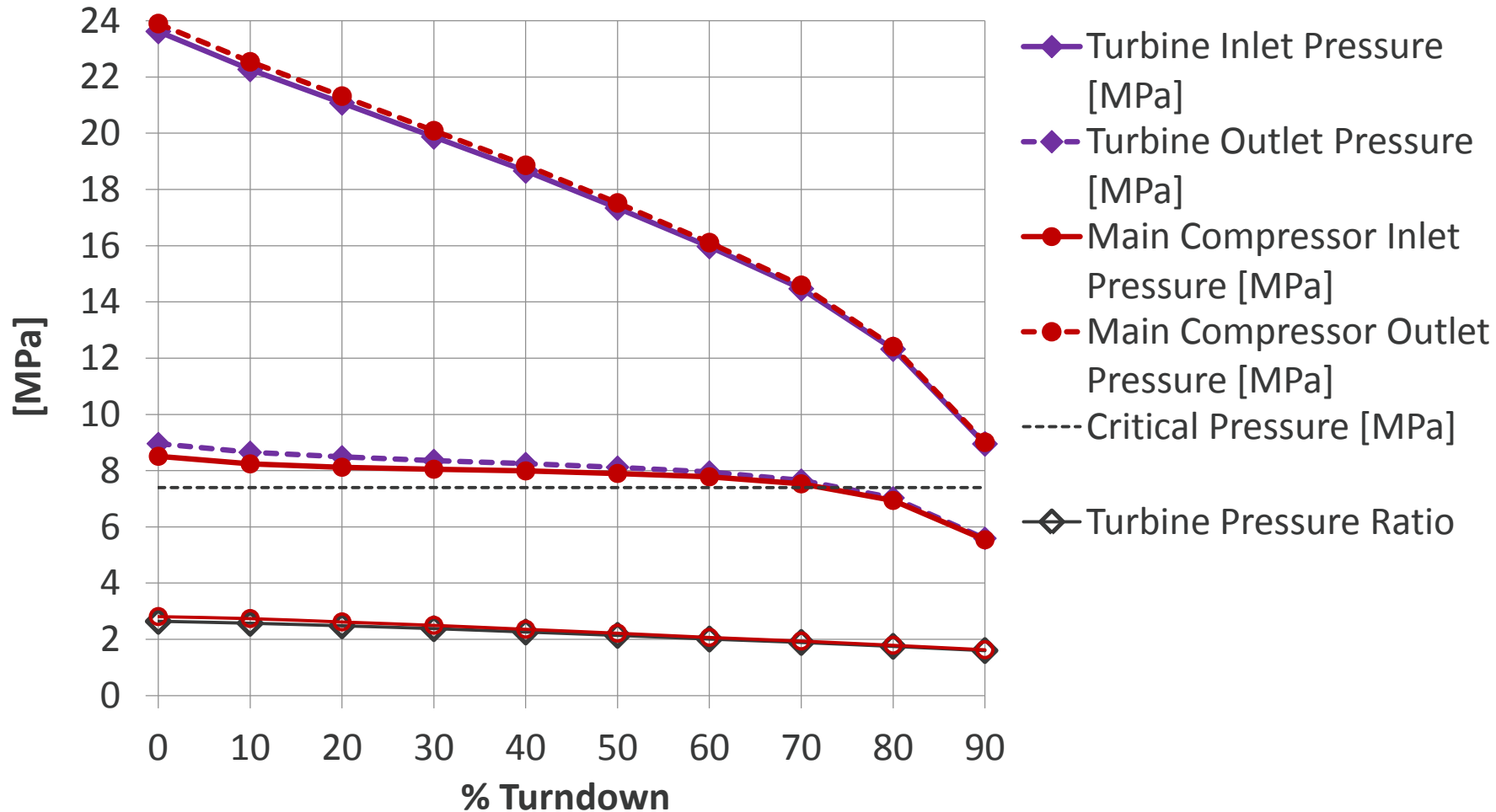
Compressor Surge Margin Results



Heat Input Turndown - Decoupled Turbomachinery

Temperature, Flow Split, and Inventory Control

Pressure Results



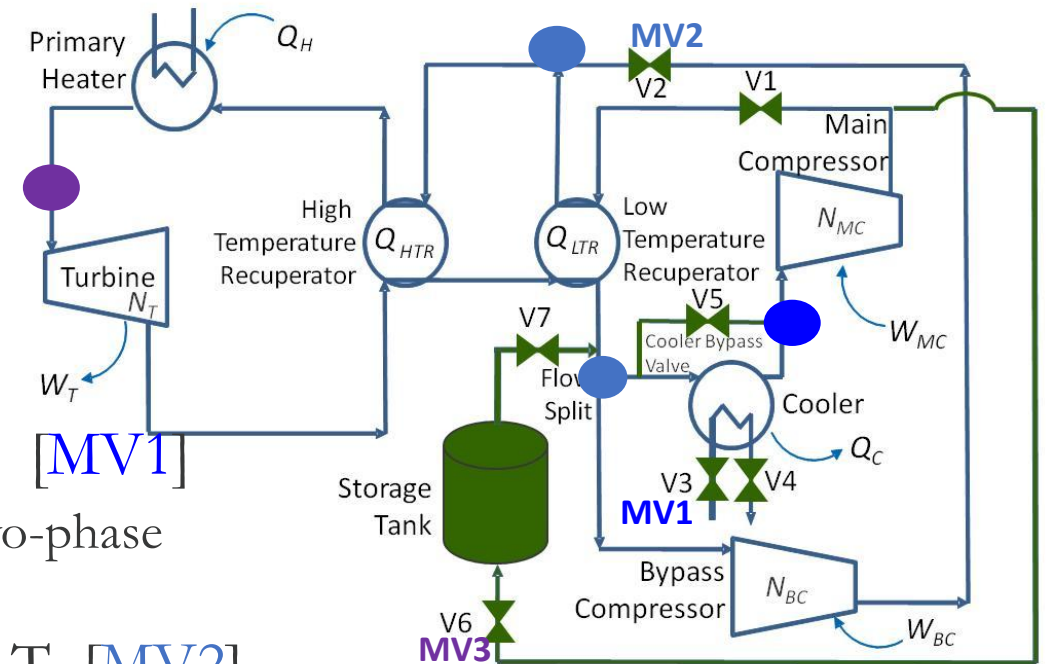
Heat Input Turndown - Coupled Turbomachinery Temperature*, Flow Split**, and Inventory*** Control

• Objective

- Maximize cycle efficiency (net power/heat input)

• Operating Constraints

- **TIT** \leq Upper bound [MV1, MV2, MV3]
 - Design point, 973.2 K (material constraint)
- Main compressor inlet T for CO₂ \geq Lower bound [MV1]
 - Design point, 308.1 K (4 K above critical T to avoid two-phase dome)
- LTR Cold Side Exit T = Bypass Compressor Exit T [MV2]
 - Surge limit for bypass compressor



• Manipulated Variables (MV) / Control Strategy

MV1: Cooling water flow (V3) / Temperature Control

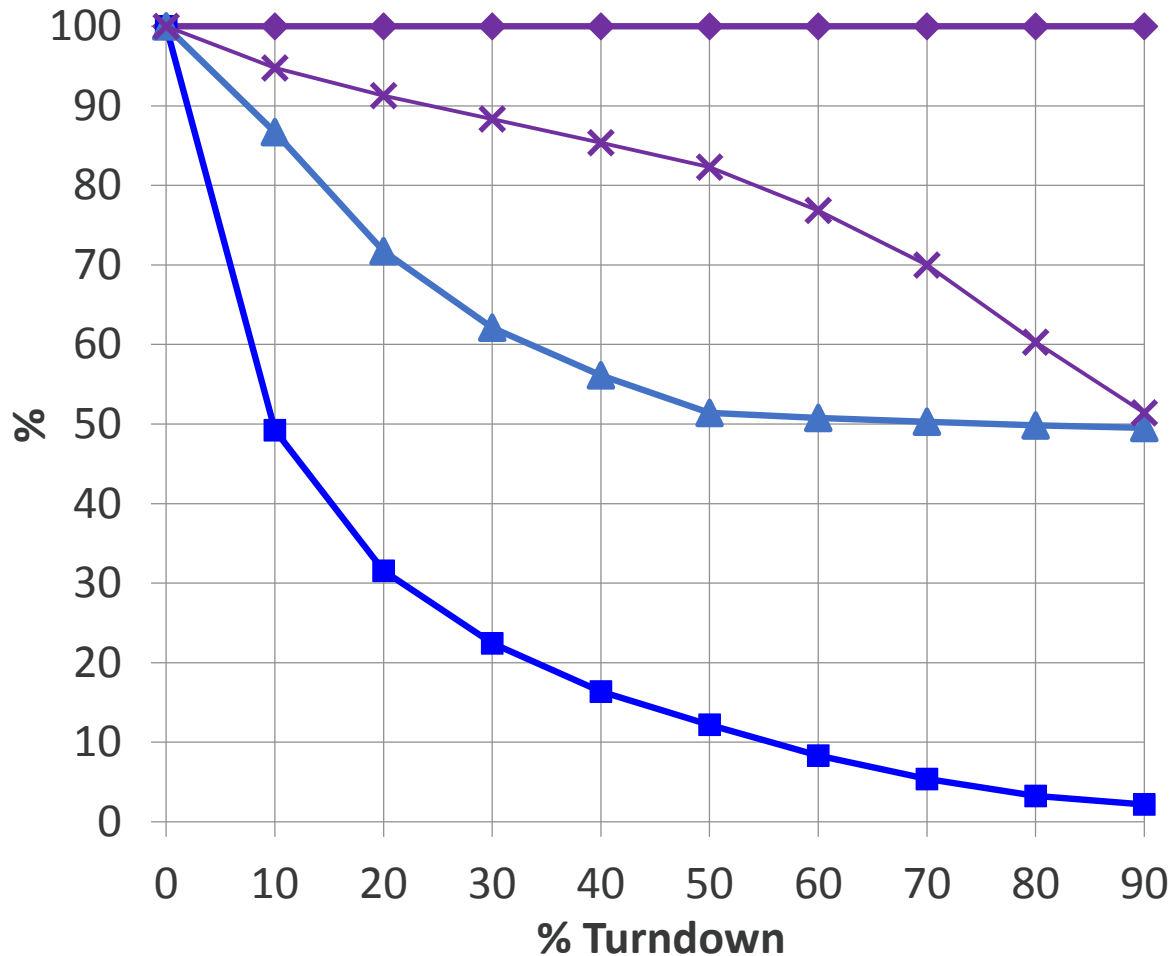
MV2: Compressor bypass (V2) / Flow Split Control

MV3: Storage valve (V6) / Inventory Control

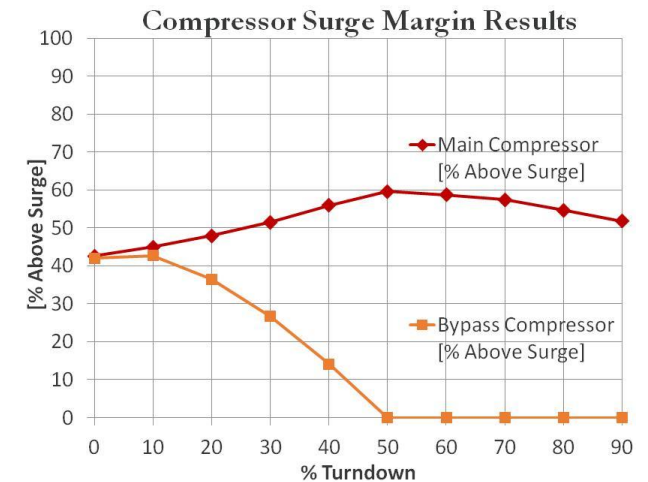
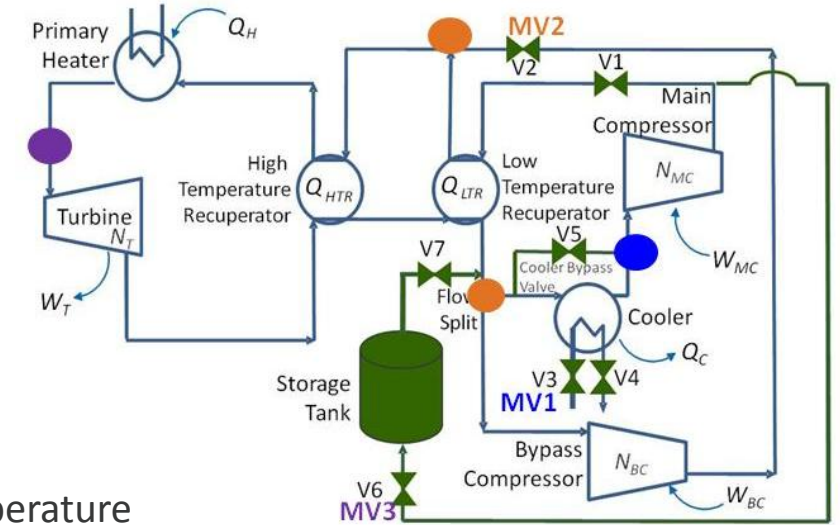
Heat Input Turndown - Coupled Turbomachinery

Temperature, Flow Split, and Inventory Control

Objective and Manipulated Variable Profiles



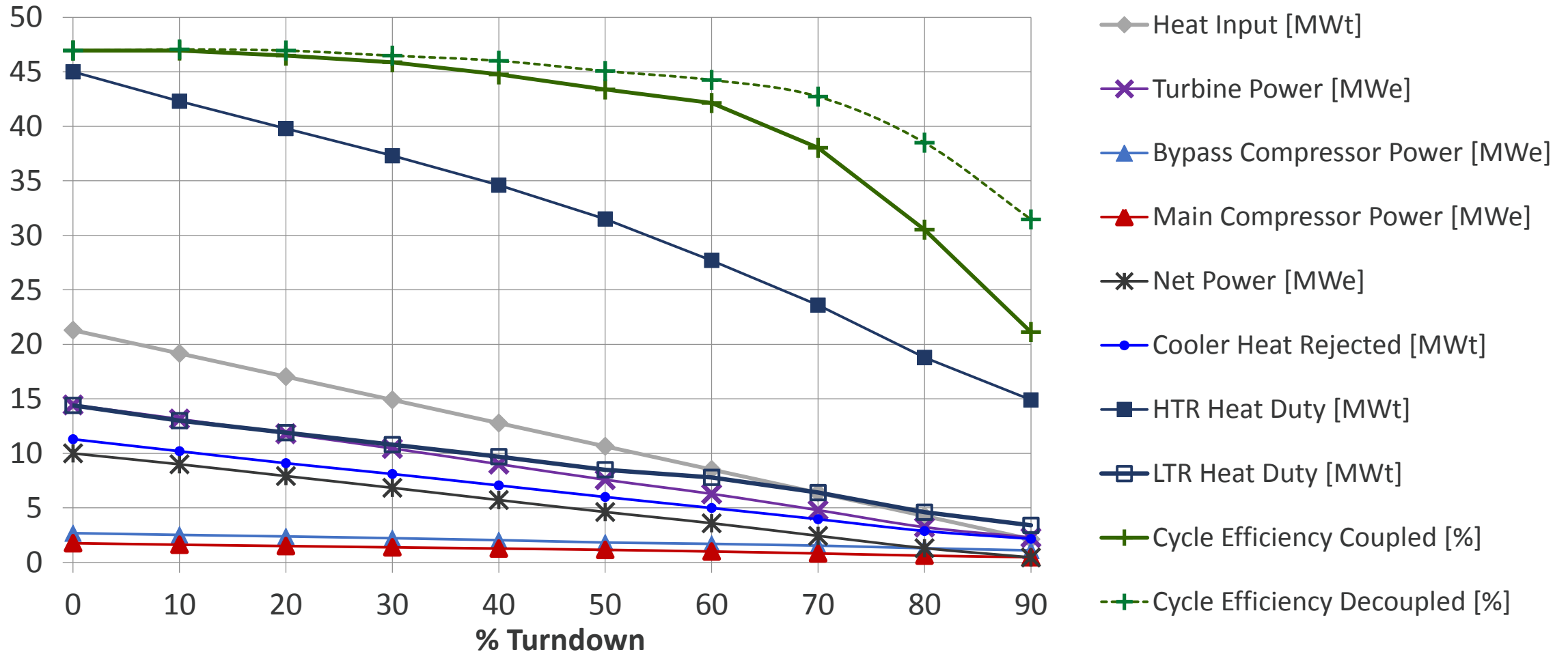
- ◆ Turbine Inlet Temperature [% of Design]
- Cooling Water Flow [% of Design]
- ▲ Compressor Bypass Valve V2 Position [% of Design]
- ✕ CO2 Storage [% of Cycle CO2 Mass]



Heat Input Turndown - Coupled Turbomachinery

Temperature, Flow Split, and Inventory Control

Power and Thermal Results



Heat Input Turndown - Coupled Turbomachinery

Temperature, Flow Split, and Inventory Control

Compressor Surge Margin Results

